MAGNETIC RECONNECTION IN LASER-DRIVEN PLASMAS: FROM ASTROPHYSICS TO THE LABORATORY *IN SILICO*

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EXECUTIVE SUMMARY

In this project, we use the state-of-the art particle-in-cell code OSIRIS to study a fundamental plasma process known as magnetic reconnection, which plays a key role in the evolution of plasmas from astrophysics to the laboratory. Reconnection is a promising candidate for producing the energetic particle distributions associated with explosive astrophysical sources; however, the particle acceleration properties of reconnection are not fully understood. Recently, laser-driven plasma experiments have been used to study reconnection in conditions relevant for astrophysics. By modeling these experiments on Blue Waters we were able to show that for current experimental conditions, electrons can be accelerated by reconnection with sufficient quantity and energy to be detected in the laboratory, which opens the way for new experimental studies of particle acceleration from reconnection. We are also working on developing a new simulation method called simplex-in-cell, which may improve the accuracy and reduce the expense of plasma simulations.

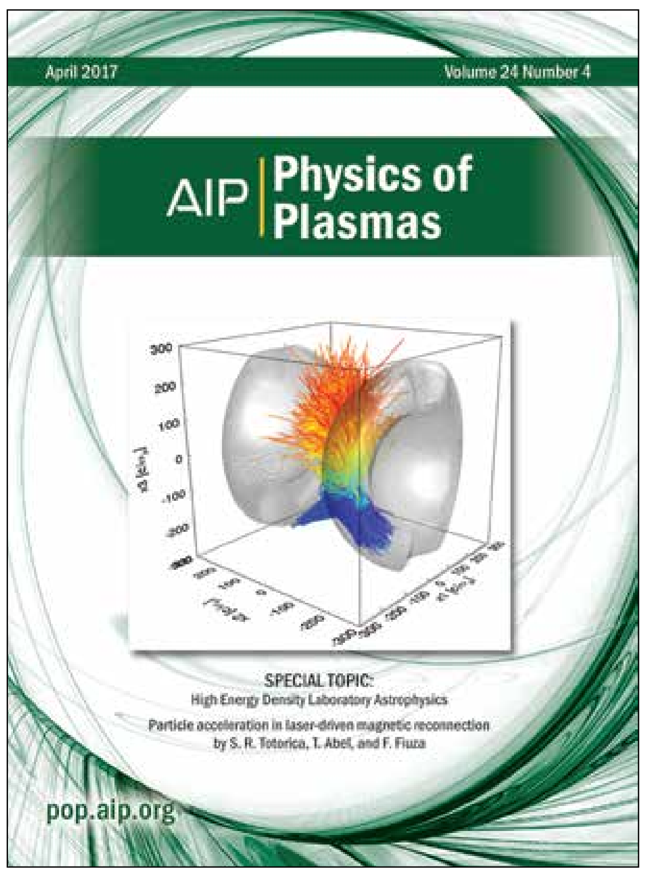

Figure 1: Cover of the April 2017 edition of *Physics of Plasmas*, showing a 3D visualization of a simulation of laser-driven magnetic reconnection. The trajectories of the energetic electrons are colored by their energy and plotted over an isocontour of the magnetic field (gray).

RESEARCH CHALLENGE

Magnetic reconnection is a fundamental plasma process that converts magnetic field energy into plasma kinetic energy though the breaking and rearrangement of magnetic field lines [1]. It is believed to play a key role in frontier problems in physics including the origin of cosmic rays, and is relevant for applications with societal benefit such as space weather and nuclear fusion energy. In astrophysics, reconnection is currently being studied intensely as a promising candidate for producing the energetic particle distributions associated with explosive astrophysical sources such as gamma-ray bursts and jets from active galactic nuclei. However, the efficiency of reconnection in accelerating nonthermal particles, and how this depends on the plasma conditions, remains poorly understood. It is currently an active area of research to determine whether reconnection can account for the astrophysical observations. As a result of the inertial confinement fusion program, high-energy laser facilities have been developed that can produce extremely hot and dense plasmas that reach a regime where scaling laws allow comparisons with astrophysical systems. The goal of this project is to use simulations to study particles from reconnection in varied plasma conditions, and in particular to investigate whether laser-driven plasma experiments could be used to study the particle acceleration properties of reconnection in the laboratory.

METHODS & CODES

One of the most powerful tools for *ab initio* plasma simulation is the particle-in-cell (PIC) method, which treats the plasma as a collection of discrete simulation particles that interact via self-consistent electromagnetic forces. The simulations for this project were run using the state-of-the-art, massively parallel, and fully relativistic PIC code OSIRIS [2] and match the experimental conditions produced by the most energetic laser systems in the world, such as the National Ignition Facility.

RESULTS & IMPACT

From the results of these simulations we were able to show clearly that for current experimental conditions, electrons can be accelerated by reconnection with sufficient quantity and energy to be detected in the laboratory. For the conditions of recent experiments, the nonthermal electrons can be accelerated to energies more than an order of magnitude larger than the initial thermal energy. The nonthermal electrons are primarily accelerated by the reconnection electric field near the X-points, which establishes a distribution of energies that resembles a power-law spectrum. After being energized, the electrons can also become trapped inside the plasmoids (magnetic islands) that form in the current layer and gain additional energy from the electric field arising from the motion of the plasmoid. By comparing simulations for finite and infinite periodic systems, we were able to demonstrate the importance of particle escape on the shape of the spectrum.

Based on our findings, we derived an analytical estimate of the maximum electron energy and a threshold condition for observing suprathermal electron acceleration in terms of the initial plasma conditions, which can now be tuned in future experiments to optimize the particle acceleration. Through the use of 3D simulations (Fig. 1) we studied the angular distribution of the accelerated particles and constructed synthetic detector spectra to determine experimental signatures. These results provide new insight into the physics of reconnection and particle acceleration, and are now helping to guide several experimental programs in the United States.

Due to limitations such as noise from artificial two-body collisions and the computational expense associated with the large number of particles required to accurately capture the development of nonthermal tails in the particle distribution, multiscale PIC simulations such as those used to study laser-driven reconnection are extremely challenging. It is thus critical to work on improved methods that could reduce the computational expense of these simulations and improve their physical accuracy. To this end, we are also developing a novel method for plasma simulation, which we refer to as simplex-in-cell (SIC). The foundation of SIC is an interpretation of the simulation particles as the vertices of an unstructured mesh that traces the evolution of the plasma distribution function in phase space [3]. This enables a new discretization using deformable phase space volume elements rather than fixed-shape, localized particles. We are using the SIC interpretation of the simulation particles for data analysis and visualization of standard PIC simulations performed using OSIRIS, and have been able to show that in certain regimes SIC can reach a given noise level using one thousand times fewer simulation particles than standard methods (Fig. 2). Future work will involve implementing SIC directly in the simulations to reduce noise and unphysical artifacts.

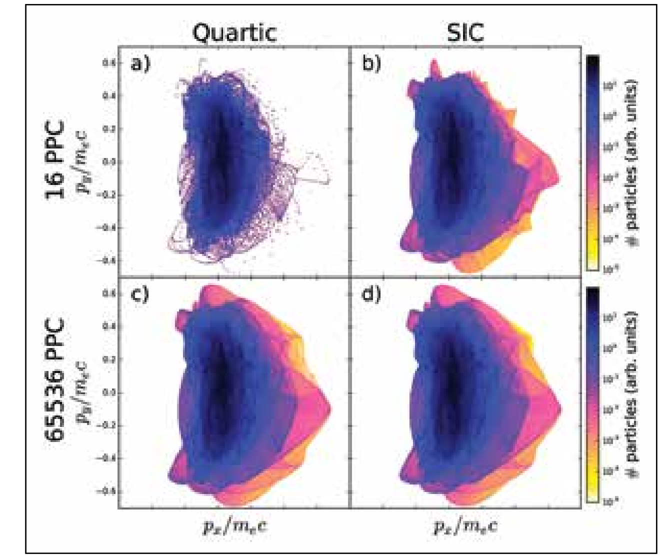

Figure 2: Momentum space for simulations of the Weibel instability with 16 particles-per-cell (PPC) (top) and 65,536 PPC (bottom). The SIC (simplex in cell) deposit (right) captures the tails and shape of the distribution at low PPC much better than a high-order (quartic) particle deposit (left).

WHY BLUE WATERS

This project required the use of large-scale 2D and 3D simulations with sufficient size and resolution to bridge the multiscale physics, from fluid dynamics to the kinetic microscopic processes. These computationally demanding simulations can require billions of simulation particles, and demand the cores, memory, and communication performance available on Blue Waters. The quick support from the NCSA staff on technical issues helped me to maximize my productivity on the machine.

PUBLICATIONS AND DATA SETS

Totorica, S. R., T. Abel, and F. Fiuza, Nonthermal electron energization from magnetic reconnection in laser-driven plasmas. *Physical Review Letters*, 116 (2016), DOI:10.1103/PhysRevLett.116.095003.

Totorica, S. R., T. Abel, and F. Fiuza, Particle acceleration in laser-driven magnetic reconnection. *Physics of Plasmas*, 24 (2017), DOI:10.1063/1.4978627.

Samuel Totorica, a fifth-year Ph.D. student in physics at Stanford University, is working under the direction of Tom Abel and Federico Fuiza. He expects to graduate in 2018.